

Technology and time scales in Photonic Doppler Velocimetry (PDV)

2024 PDV workshop
Las Vegas, NV



Institute for Shock Physics (WSU, Pullman WA)



DCS@APS (Argonne IL)



Applied Science Laboratory (Spokane WA)

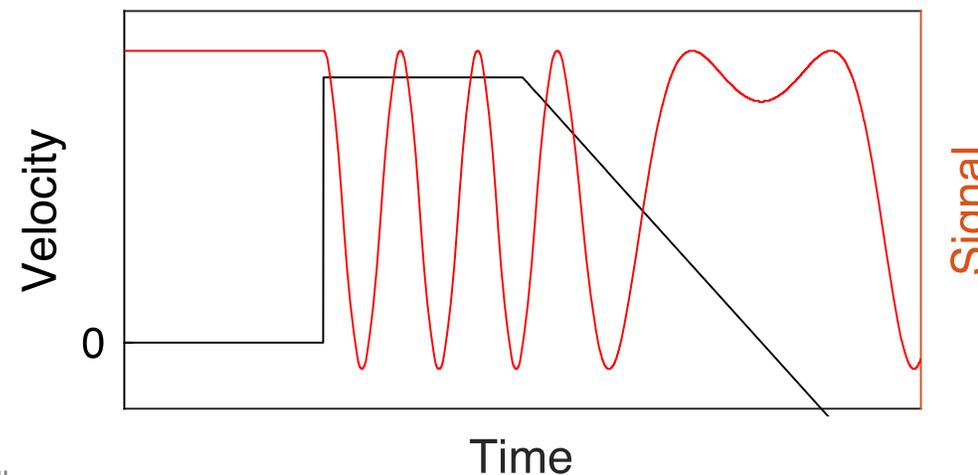
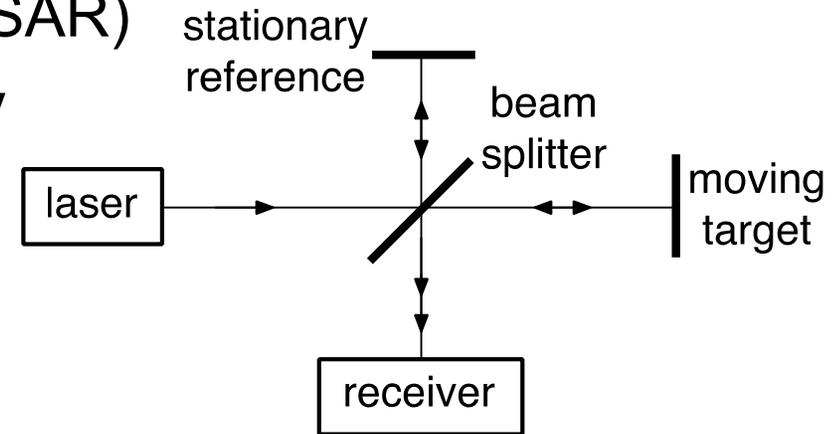
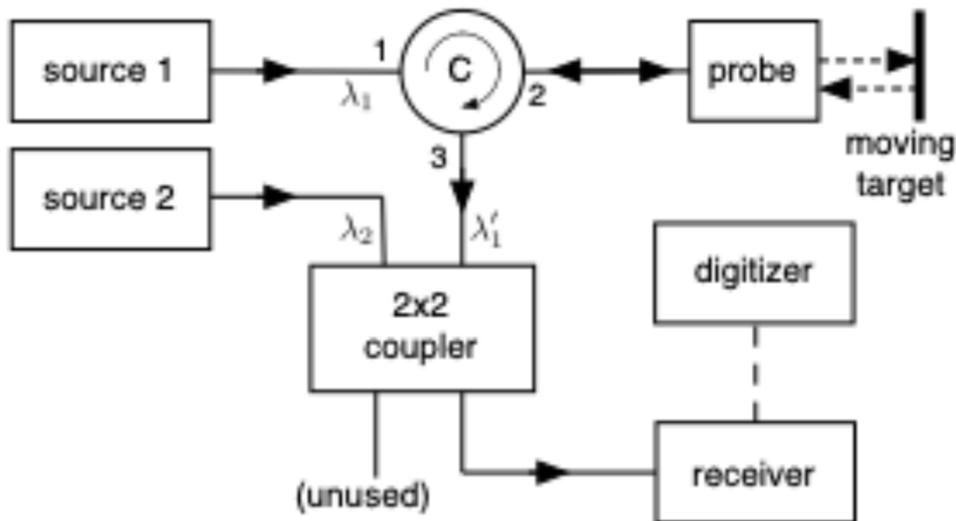
D.H. Dolan

Outline

- What makes PDV work?
 - How is PDV different from other diagnostics?
 - Some practical details
- Measuring Doppler shift
 - Local FFTs in a nutshell
 - **Limiting uncertainty is a $-3/2$ power of local analysis duration**
 - Anything that promises better is a misunderstanding or a lie
 - It is always possible to do worse

How is PDV different from other diagnostics?

- Doppler shift used in other techniques (VISAR)
- PDV encodes velocity in signal **frequency**
- PDV is almost exclusively fiber based
 - Measurements tend to be **shorter/**
faster/more destructive than LDV



Some practical details

- Beat frequency scales with wavelength
 - 1.29 GHz for every 1 km/s at 1550 nm
- Signal amplitude scales with square root of target and reference power
 - 100x return = 10x signal
- Signal noise scales with square root of reference power
 - More reference power helps, to a point

$$\Delta B = \frac{2}{\lambda_1} \Delta v$$

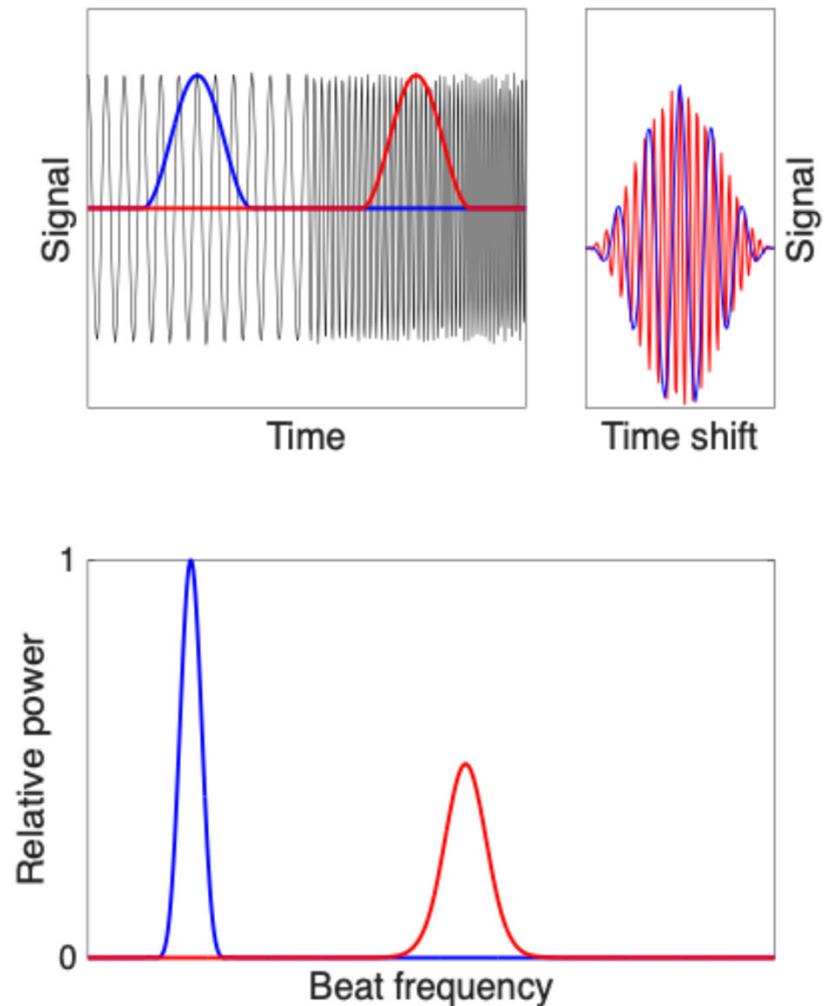
$$A \propto \sqrt{P_1 P_2}$$

$(P_2 \gg P_1)$

$$\sigma \propto \sqrt{P_2}$$

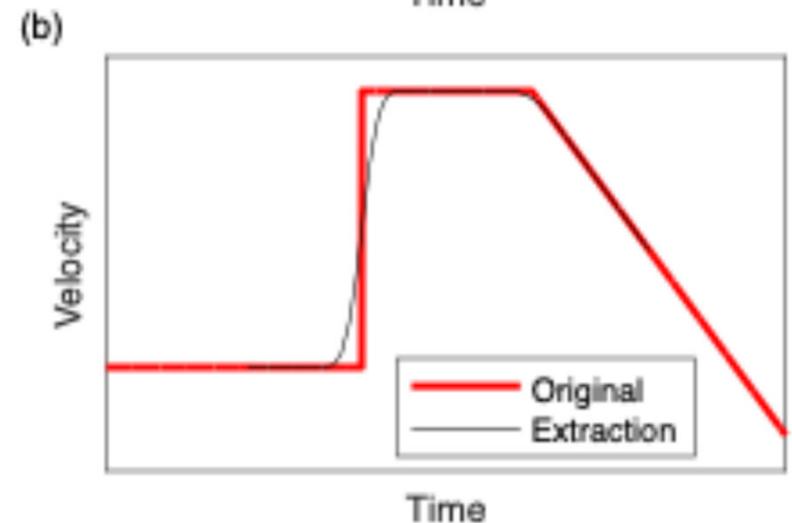
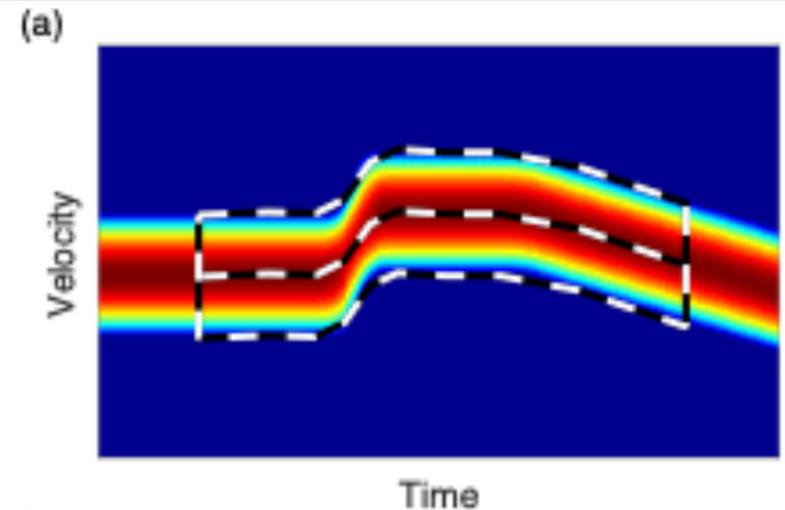
Local FFTs in a nutshell

- Given a PDV signal:
 - Apply a local window function, e.g. Hann
 - Zero pad windowed signal
 - At least the next power of two
 - Probably much more
 - Apply the Fast Fourier Transform
 - Map from time to frequency domain
- Repeat this process many times throughout the signal



Storing the results of local FFT analysis

- Spectrograms
 - Keep every FFT as an image slice
 - Visually appealing (with log scaling)
 - Can be **enormous** (giga/tera/petapixels)
 - Hard to use quantitatively
- Histories
 - Keep only the points of maximum power
 - Usually requires **ROI selection**
 - Connect those points to trace out velocity of interest (usually what we want)
 - Can be **misleading/unphysical**



Measurement time scales

- Total measurement duration: Δ
 - How much of the experiment do you really care about?
 - Usually less than recorded signal (digitizers have **deep** memory)
- Advance increment: δ
 - How much time between local FFT?
 - Sets temporal mesh, not limiting rise time
 - Can be as small as sample intervals, if you are patient
- Analysis duration: τ
 - How much signal is used in each FFT
 - Sets limiting rise time ($\sim 1/3$ duration)
 - Digital window shape plays a role

$$\delta \leq \tau \ll \Delta$$

Limiting uncertainty

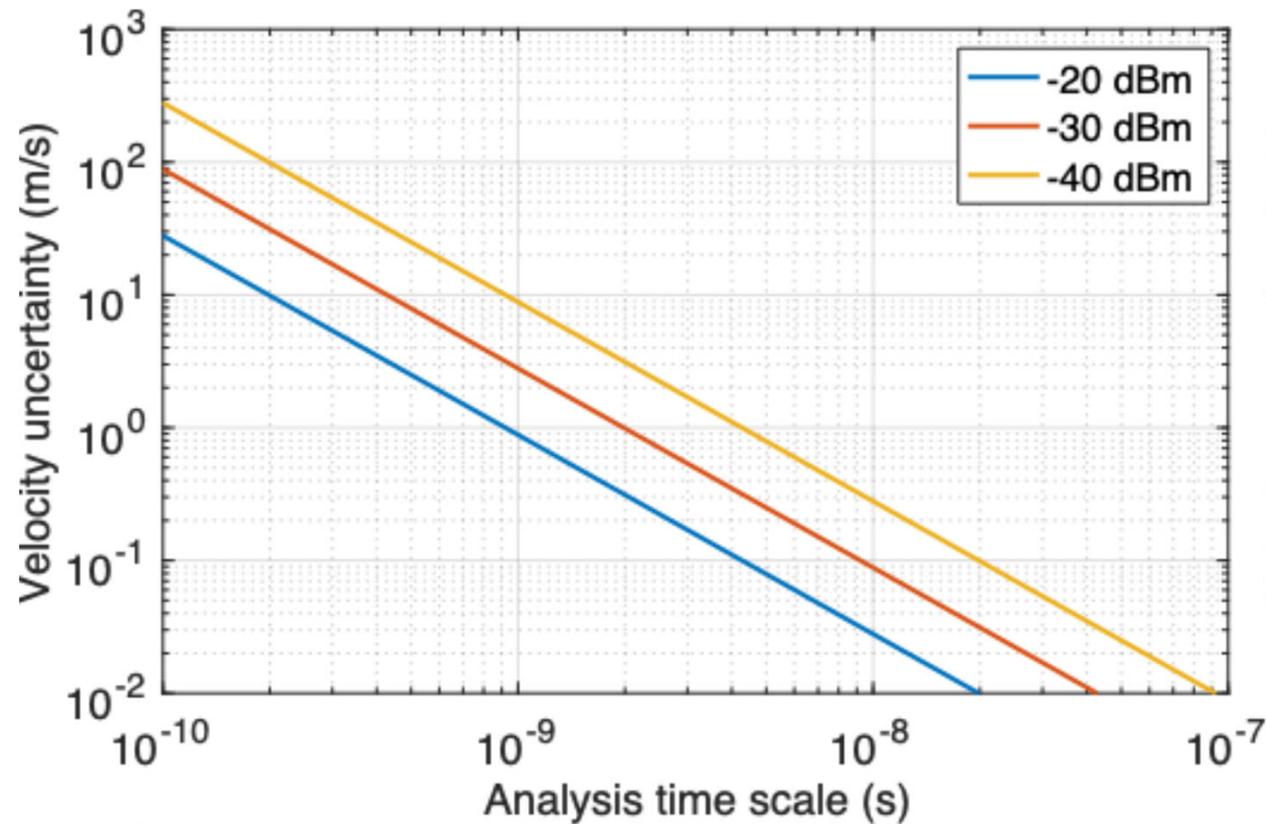
- Peak position can be determined to better than the peak **width**
 - Classic uncertainty principle
- What matters:
 - Analysis duration
 - Sample rate
 - Noise fraction
 - Limited by **target power**

$$\sigma_B \geq \sqrt{\frac{6}{f_s \tau^3} \frac{\sigma_s}{A_s} \frac{1}{\pi}}$$

$$\sigma_v \geq \frac{1}{2\pi} \sqrt{\frac{\lambda h c}{P_1 \tau^3}}$$

What does all this mean?

- 1 μW (-30 dBm) return
 - 1 ns: < 3 m/s
 - 10 ns: < 0.1 m/s
- More power helps, but...
 - Burn/SBS limits
 - Different probe design
 - 10-60 dB range
 - Signal stability problems
- Time scale is the big lever
 - Many ns: life is good
 - Sub-ns: life is challenging



Summary

- PDV encodes velocity as signal frequency
 - Doppler shift is measured from local beat frequency
- Time scales are everything
 - Analysis duration sets limiting rise time
 - Example: 10 ns FFT is nominally 3 ns (10-90%)
 - Limiting uncertainty is a **-3/2 power of analysis duration**
- References
 - D.H. Dolan, “Extreme measurements with Photonic Doppler Velocimetry (PDV)”, Review of Scientific Instruments **91**, 051501 (2020).
 - D. H. Dolan, “Technology and times scales in Photonic Doppler Velocimetry (PDV)”, Measurement Science and Technology **35**, 061001 (2024).

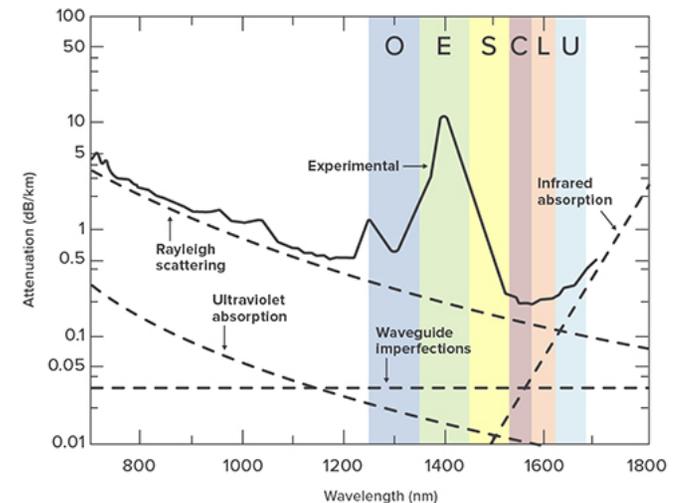
Extra slides



What is so special about 1550 nm?

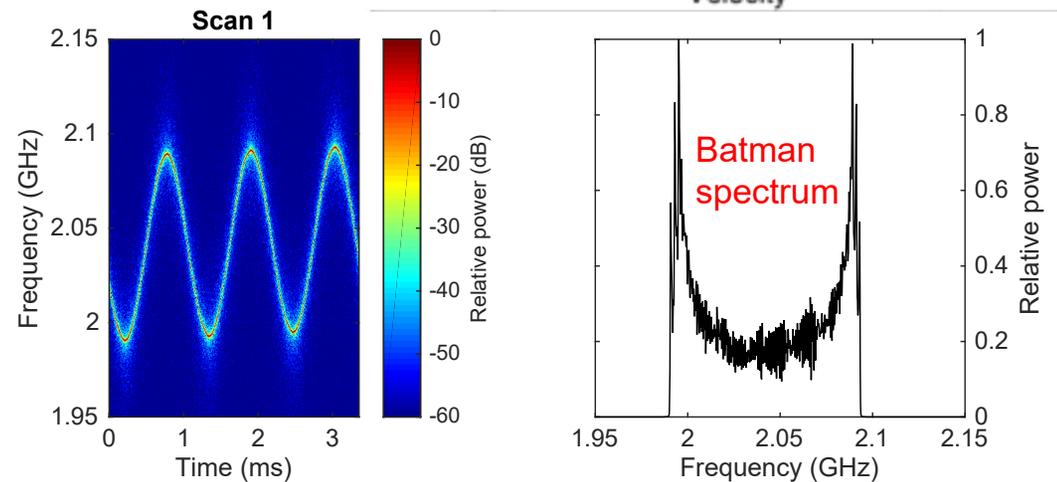
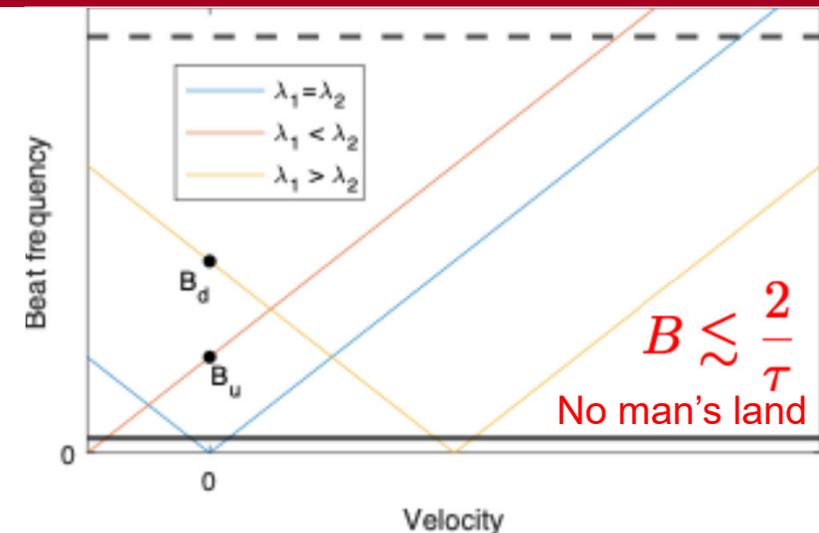
- Silica transparency
- Erbium-doped fiber amplification
- Industry investment
 - SMF28 (single mode) fiber
 - Lasers, detectors, circulators...
- Other wavelengths can be used
 - 1310 nm (SM28 compatible)
 - 1064 nm (tunable lasers)
 - 775 nm (doubled 1550 nm)
 - 532 nm (possible but tricky)
 - Almost anything open beam...

Not SMF28



Technology and time scales

- Short measurements (< 10 us)
 - Move away from $B=0$
 - Offset $> 2/(\text{smallest analysis duration})$
 - Usually based on two lasers
- Long measurements ($\gg 10$ us)
 - AO shifting, active locking, or beat monitoring
- PDV systems built around experimental requirements
 - Fast tends to be short
 - Long tends to be slow



FFT spectral width

$$\text{width} \geq \frac{C[w(t)]}{\tau}$$

- Minimum width set by analysis duration
 - Uncertainty principle
- Additional broadening
 - Acceleration/chirp
 - Velocity distributions
- Histories based on several discrete velocity **assumptions**
 - One Doppler shift per peak
 - Peaks are well separated
 - Changes are slow compared to analysis duration

